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(54) **METHOD OF AND APPARATUS FOR DETERMINING A ROTOR DISPLACEMENT PARAMETER**

**VERFAHREN UND VORRICHTUNG ZUR BESTIMMUNG EINES
ROTOR-VERSTELLUNGS-PARAMETERS**

PROCEDE ET APPAREIL POUR DETERMINER UN PARAMETRE DE DEPLACEMENT DE ROTOR

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Description

This invention relates to a method of and apparatus for determining a rotor displacement parameter (such as position or speed) for an electric motor, and to apparatus incorporating the electric motor. The invention has particular application to the continuous determination, by electrical rather than mechanical means, of rotor angular position, and the use of such position data in controlling the electric motor.

Many types of electric motor incorporate an electronic commutator which adjusts the winding excitation according to the instantaneous position of the rotor. The position of the rotor may be determined mechanically, but is advantageously deduced from the motor's current and voltage waveforms. Mechanical determination can involve complex and expensive equipment, and may detrimentally affect the rotor's inertia and friction characteristics.

A paper entitled "Application of stochastic filtering to a permanent magnet synchronous motor-drive system without electro-mechanical sensors", by Dhaouadi, R. *et al.* (Proc. ICEM, Boston, 1990) discloses a method of determining rotor position which involves detecting electrical characteristics (phase voltages and currents) of the motor at given instants and estimating rotor position from these characteristics using an extended Kalman filter algorithm. An initial estimate of rotor position is provided by solving the mechanical equation of motion for the rotor. Phase flux linkage, the value for which is utilised in the determination of rotor position, is modelled as being linearly dependent on phase current.

A paper entitled "A state observer for variable reluctance motors: analysis and experiments", by Lumsdaine, A. *et al.* (Proc. ASILOMAR Conference on Circuits, Systems and Computers, Pacific Grove, 1985) discloses a similar method in which rotor position is estimated from the electrical characteristics using a state observer model.

The disadvantages with these techniques are that they are limited to specific types of electric motor and that they are limited to specific operating condition ranges.

The present invention seeks to solve these problems. In its various aspects, the invention provides techniques which can be applied to virtually any type of motor having phase flux linkage varying with rotor position. Such motor types include switched and variable reluctance motors, hybrid stepping motors, permanent magnet synchronous motors, brushless alternating and direct current motors, and sinusoidal and trapezoidal permanent magnet motors. In particular, the invention can be applied to any motor which is controlled in dependence on rotor position (so called "rotor position switched drives"). Other arrangements are described below.

International Patent Application No. PCT/SE90/00498 describes an arrangement in which magnetic flux in a motor is compared with tabulated values of a non linear function of magnetic flux with respect to current.

IEEE Transactions on Industry Applications Vol. 27 No. 5 pages 1005-1011 describes a controller for use to control motor speed without the need for a sensor. Two line voltages and stator currents are employed to compute a flux linkage space vector. An indication of angular velocity is then computed using the phase angle of the vector and the rate of change of flux linkage.

US-A-5107195 describes an apparatus and method which simultaneously senses phase current and phase flux, determines the reluctance of the stator-to-rotor air gap and evaluates the position of the rotor phase with respect to the stator pole tips.

A paper by Chow and Thomas, published in 1988 IEEE Conference Proceedings, Southeastcon, at pages 523 to 528, describes a method for detecting a variable reluctance machine's rotor position using a predictor/estimator. The arrangement requires a shaft encoder.

According to a first aspect of the present invention, there is provided a method of determining a rotor displacement parameter of the rotor of an electric motor, the method comprising the steps of: measuring electrical characteristics of the motor at given instants; obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants; obtaining an estimate of at least one of the electrical characteristics on the basis of said first estimate of said parameter and the measured electrical characteristics; and, obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of at least one of the electrical characteristics and the measured value of said at least one electrical characteristic.

By predicting an updated value of the parameter by extrapolation, rather than, as in the prior art, by solving the equation of motion for the rotor, the present invention can provide an estimate of the value which is not dependent directly on the mechanical properties of the motor. This has several advantages. Firstly, these properties do not have to be predetermined at any stage. Secondly, if (as is often the case) the mechanical properties of the motor (such as inertia, friction or load torque) actually change during operation, account is automatically taken of these changes.

Said measured electrical characteristics may comprise the voltage and current of a phase of the electric motor, said at least one electrical characteristic being the phase current, the method preferably comprising the step of: obtaining an estimate of the phase flux linkage on the basis of said measured voltage and current; said estimate of the phase flux linkage being used with the first estimate of said parameter to provide the estimate of the phase current. The method may comprise the further step of: correcting the estimate of the phase flux linkage on the basis of the difference between the corrected estimate of said parameter and said first estimate of said parameter; said corrected

estimate of the phase flux linkage being used to provide the estimate of the phase current. Alternatively, the method may comprise the further step of: correcting the estimate of the phase flux linkage on the basis of the difference between the measured value of the phase current and the estimated value of the phase current; said corrected estimate of the phase flux linkage being used to provide the estimate of the phase current.

For the sake of accuracy, the first estimate of said parameter is preferably obtained on the basis of the values of the parameter at the three immediately preceding instants. It may be predicted in accordance with an equation of the form $\underline{a}_k = 3a_{k-1} - 3a_{k-2} + a_{k-3}$, where \underline{a}_k is the updated value, and a_{k-1} , a_{k-2} and a_{k-3} are the values of the parameter at three preceding instants.

Said parameter may be the angular displacement of the rotor.

According to a second aspect of the present invention, there is provided a method of determining a rotor displacement parameter for an electric motor, the method comprising the steps of: measuring an electrical characteristic of the motor at a given instant; predicting a value representative of flux linkage from the characteristic; correcting the predicted flux linkage value in dependence on the difference between the actual value of the characteristic and a value estimated using the predicted flux linkage value; and, determining the rotor displacement parameter using the corrected flux linkage value.

This aspect of the present invention arises from the discovery, pursuant to this aspect of the present invention, that such flux linkage correction can be important in reducing inaccuracies in the estimation of rotor position. This is because flux linkage is conventionally determined from measured voltage and current values by integration. Measurement and other errors can cause the flux linkage values to drift, unless corrected.

It will be appreciated that the corrected flux linkage value may not be used in the determination of the rotor displacement parameter at the given instant. In the preferred embodiment, in fact, the corrected value is not so used until the next instant at which a determination of the parameter is effected.

Two alternative ways of correcting flux linkage values are described later. One involves comparing directly measured values of current and values estimated using the predicted flux linkage value. The other involves a comparison between mechanical and electrical estimates of rotor position which implicitly involves a comparison between measured and predicted current values.

Whichever alternative is adopted, it is preferred that the correction is determined in dependence on said difference multiplied by the differential of flux linkage with respect to current. The dependence may either be directly on said difference multiplied by the differential of flux linkage with respect to current, or may be indirect, via the differential of flux linkage with respect to rotor position multiplied by the difference between the two estimates of rotor position. Such an arrangement can provide a simple but effective way of correcting flux linkage.

Preferably, the correction is determined from the difference between the actual and estimated values of such electrical characteristic for a plurality of phases of the motor. Employing information from some or possibly even all of the phases of the motor rather than just one phase can ensure a more accurate estimate of the rotor displacement parameter.

Values representative of the non-linear variation of flux linkage with current may be stored and employed in the determination of the parameter value. A value representative of current may be estimated from flux linkage according to said stored representative values, and the parameter value determined in dependence on the estimated current value.

The invention extends to a method for controlling an electric motor, wherein the motor is controlled in dependence on the value of the rotor displacement parameter determined as described above. The rotor displacement parameter information may alternatively or additionally be output as an output signal, for example, to be used for displaying rotor position or speed.

The above described method may be applied to determining the rotor displacement parameter for an electric motor having a plurality of windings sharing a common connection, wherein the electrical characteristics are measured from points other than the common connection. It has been found that in order to determine the rotor displacement parameter, the electrical characteristics need only be detected at the external or outer nodes of the windings, and not at their common connection. This is advantageous since the common connection on motor windings is often inaccessible. This aspect of the invention has particular relevance to a motor having star-connected windings.

According to a third aspect of the present invention, there is provided apparatus for determining a rotor displacement parameter of a rotor of an electric motor, the apparatus comprising: means for measuring electrical characteristics of the motor at given instants; means for obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants; means for obtaining an estimate of at least one of the electrical characteristics on the basis of said first estimate of said parameter and the measured electrical characteristics; and, means for obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of at least one of the electrical characteristics and the measured value of said at least one electrical characteristic.

According to a fourth aspect of the present invention, there is provided apparatus for determining a rotor displacement

ment parameter of a rotor of an electric motor, the apparatus comprising: means for measuring the voltage and current of a phase of an electric motor at given instants; means for obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants; means for obtaining an estimate of the phase flux linkage on the basis of said measured voltage and current; means for obtaining an estimate of the phase current on the basis of said first estimate of said parameter and the estimate of the phase flux linkage; and, means for obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of the phase current and the measured value of the phase current.

According to a fifth aspect of the present invention, there is provided apparatus for determining a rotor displacement parameter for an electric motor, the apparatus comprising: means for measuring an electrical characteristic of the motor at a given instant; means for predicting a value representative of flux linkage from the characteristic; means for correcting the predicted flux linkage value in dependence on the difference between the actual value of the characteristic and a value estimated using the predicted flux linkage value; and, means for determining the rotor displacement parameter using the corrected flux linkage value.

The various aspects of the invention may be provided in any combination one with another.

Preferred features of the invention, the theory underlying the invention, and examples of the operation of the invention are now described with reference to the accompanying drawings, in which:

Figure 1 is a block diagram of apparatus for determining rotor position for an electric motor;

Figure 2 is a block diagram representing a method of determining rotor position;

Figure 3 is a sketch of star-connected windings of an electric motor;

Figures 4 show experimental results obtained using the present invention for an electric motor accelerating from rest with no current control; and

Figures 5 show experimental results for the same electric motor but with current control.

A basic embodiment of the invention relating to a permanent magnet (PM) motor is first described, followed by a more generally applicable modified embodiment. In both embodiments, a predictor/corrector technique is employed to determine the angular position of the rotor of an electric motor. Such a technique requires a mathematical model (an "observer") of the relevant characteristics of the motor. For each embodiment, the model is described first, and then the use of that model in the determination of rotor position is described.

MOTOR MODEL FOR THE BASIC EMBODIMENT

Considering firstly the model for the basic embodiment, the voltage equation for a 3-phase balanced PM alternating current motor are expressed in matrix form as:

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} \quad (1)$$

where v_1 , v_2 and v_3 are the phase voltages, R is the resistance of the stator winding, i_1 , i_2 and i_3 are the phase currents, and ψ_1 , ψ_2 and ψ_3 are the phase flux linkages of the windings.

The general flux linkage variables may be defined in the form:

$$\begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} L_{11}(\theta) & M_{12}(\theta) & M_{13}(\theta) \\ M_{21}(\theta) & L_{22}(\theta) & M_{23}(\theta) \\ M_{31}(\theta) & M_{32}(\theta) & L_{33}(\theta) \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \begin{bmatrix} \lambda_m(\theta) \\ \lambda_m(\theta - \frac{2\pi}{3}) \\ \lambda_m(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad (2)$$

Here, θ is electrical angular position, λ_m , the magnet flux linkage, is a function of θ , $L_{xx}(\theta)$ is the self inductance of winding x , and $M_{xy}(\theta)$ is the mutual inductance between two windings x and y .

It will be appreciated that the inductance matrix in Equation 2 describes the self and mutual inductance relationships of the stator phases of a symmetrical PM motor. Differentiating Equation 2, substituting it into Equation 1, and rearranging,

$$\begin{aligned}
 \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} &= \begin{bmatrix} L_{11}(\theta) & M_{12}(\theta) & M_{13}(\theta) \\ M_{21}(\theta) & L_{22}(\theta) & M_{23}(\theta) \\ M_{31}(\theta) & M_{32}(\theta) & L_{33}(\theta) \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \\
 + \frac{d}{dt} \begin{bmatrix} L_{11}(\theta) & M_{12}(\theta) & M_{13}(\theta) \\ M_{21}(\theta) & L_{22}(\theta) & M_{23}(\theta) \\ M_{31}(\theta) & M_{32}(\theta) & L_{33}(\theta) \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} &= \frac{d}{dt} \begin{bmatrix} \lambda_m(\theta) \\ \lambda_m(\theta - \frac{2\pi}{3}) \\ \lambda_m(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad (3)
 \end{aligned}$$

For a machine which has no variable inductance, Equation 3 can be rearranged to give more simple system equations. Linear 3-phase coupled systems are magnetically symmetrical if the diagonal elements of the inductance matrix are equal. Assuming further that there is no change in the rotor reluctance with angle, then:

$$\begin{aligned}
 L_{11} &= L_{22} = L_{33} = L_1 \\
 M_{12} &= M_{21} = M_{13} = M_{31} = M_{23} = M_{32} = M_1
 \end{aligned} \quad (4)$$

In the star-connected with isolated star point motor:

$$i_1 + i_2 + i_3 = 0 \quad (5)$$

Hence,

$$\begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} - \begin{bmatrix} \lambda_m(\theta) \\ \lambda_m(\theta - \frac{2\pi}{3}) \\ \lambda_m(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad (6)$$

where $L = L_1 - M_1$

Differentiating Equation 6, substituting into Equation 1 and rearranging,

$$\begin{matrix} 5 \\ 10 \end{matrix}
 \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} \lambda_m(\theta) \\ \lambda_m(\theta - \frac{2\pi}{3}) \\ \lambda_m(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad (7)$$

As explained in later sections, position estimation based on the flux linkages is achieved by Equation 2 or Equation 6 according to whether the machine has variable winding inductances or constant inductances. Direct measurement of phase current and phase voltage can allow estimation of the flux linkage. If the terminal phase voltages of the motor are sensed and stator voltage drops are subtracted, the change of the flux linkage of each phase with time can be determined in terms of the rotor position, phase currents, and other motor parameters which appear in the right-hand side of Equation 3 and Equation 7.

20 ROTOR POSITION DETERMINATION FOR THE BASIC EMBODIMENT

The manner in which the above-described model is used to determine rotor position is now described with reference to Figures 1 and 2.

Referring first to Figure 1, apparatus for determining rotor position for an electric motor and thence controlling the electric motor comprises a permanent magnet 3-phase motor 10, a set of current transducers 12, a set of voltage transducers and attenuators 14, a position estimator 16, and a controller 18 responsive to control inputs and including a 3-phase inverter circuit 20 for providing a 3-phase power supply. The inverter circuit 20 comprises three pairs of transistors T1-T6 and associated diodes D1-D6. In the preferred embodiment, the base or gate of each transistor is provided with control signals from a hysteresis current controller. The motor 10 is driven in response to the control inputs passed to the controller 18. The controller utilises rotor position information from the rotor position estimator 16 to determine how power should be distributed to the three phases of the motor.

The operation of the position estimator 16 is now described with reference to Figure 2. In overview, the position estimator provides, at each new time instant, fresh phase flux linkage and position estimates. In Figure 2, estimated values of quantities are designated by subscript "e" whilst measured values are designated by subscript "m". The position estimator 16 is implemented, in the present embodiment, either by a Digital Signal Processor (DSP), or by an Application-Specific Integrated Circuit (ASIC) in conjunction with appropriate means for storing the information required for the operation of the position estimator. The operation of the position estimator is now described in more detail.

40 Flux Linkage Prediction

Firstly (see the INTEGRATOR box) the phase currents i_1 , i_2 and i_3 and voltages v_1 , v_2 and v_3 measured using the current and voltage transducers 12 and 14 are used to predict the phase flux linkages ψ_1 , ψ_2 and ψ_3 of the motor. It is apparent from Equation 1 that the function of flux linkage to be evaluated is of the following form:

$$\begin{matrix} 45 \\ 50 \end{matrix}
 \begin{bmatrix} \psi_1(t) \\ \psi_2(t) \\ \psi_3(t) \end{bmatrix} = \int_0^t \left(\begin{bmatrix} v_1(\tau) \\ v_2(\tau) \\ v_3(\tau) \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_1(\tau) \\ i_2(\tau) \\ i_3(\tau) \end{bmatrix} \right) d\tau \quad (8)$$

In general, the function of $(v(\tau) - Ri(\tau))$ does not have a closed form integral. Although, for cases where extremely high accuracy is required, different integration methods can be used, the relatively simple method employed in the present embodiment is integration by the rectangular rule:

$$\psi_{n(k)} = \Delta T [v_{n(k)} - R i_{n(k)}] + \psi_{n(k-1)} \quad n=1,2,3$$

$$k=1,2,\dots \quad (9)$$

where ΔT is the sampling interval and n is the number of phases in the motor. The estimates of flux linkage are designated on Figure 2 as $\psi_{1e(k)}$, $\psi_{2e(k)}$, and $\psi_{3e(k)}$.

Since the integration starts at $k = 1$, $\psi_n(0)$ plays the role of the initial condition. In PM machines, the initial value of flux linkage is defined by the position of the magnet. Therefore, to evaluate Equation 9 and to set up the initial condition, the rotor can be brought to a known position which defines the initial values ($\psi_n(0)$) of the integration.

Rotor Position Prediction

Next (see the POSITION CORRECTION AND POSITION ESTIMATION & PREDICTION box) a first estimate ($\theta_{e(k)}$) of rotor position is provided for a new time k using an extrapolation technique. The mechanical equations of motion for the motor can be written:

$$T = \frac{1}{p} \left[J \frac{d^2\theta}{dt^2} + B \frac{d\theta}{dt} + T_1 \right] \quad (10)$$

where T is the motor torque, p is the number of rotor pole pairs, J is the motor inertia, B is the motor friction and T_1 is the load torque. It can be seen from the equation that the position of the rotor changes as a second order function. Therefore, a second-order polynomial in time is fitted to the previous known rotor positions $\theta_{e(k-1)}$, $\theta_{e(k-2)}$ and $\theta_{e(k-3)}$ at times $k-1$, $k-2$ and $k-3$:

$$\theta = at_2 + bt + c \quad (11)$$

It will be appreciated that the fit is exact in the cases of constant speed and constant acceleration. Then, with $t=0$ at time step $k-3$:

$$\theta_{e(k-3)} = c; \quad \theta_{e(k-2)} = a(\Delta T)^2 + b\Delta T + c;$$

$$\theta_{e(k-1)} = 4a(\Delta T)^2 + 2b\Delta T + c; \text{ and } \theta_{e(k)} = 9a(\Delta T)^2 + 3b\Delta T + c \quad (12)$$

Eliminating the polynomial coefficients and solving for $\theta_{e(k)}$ gives the first estimate for the latest rotor position:

$$\theta_{e(k)} = 3\theta_{e(k-1)} - 3\theta_{e(k-2)} + \theta_{e(k-3)} \quad (13)$$

It will be appreciated that alternative extrapolation techniques (for example, higher order polynomials) to that described above could be used.

Current Estimation

Next (see the first CURRENT ESTIMATION box) a first estimate of phase current (i_1 , i_2 and i_3) is made based on the first estimate of rotor position and the estimate of flux linkage. If the simplifying assumptions underlying Equation 6 hold, then phase current can be estimated as follows:

$$\begin{aligned}
 i_{1e} &= [\psi_{1e} + \lambda_m (\theta_e)]/L \\
 i_{2e} &= [\psi_{2e} + \lambda_m (\theta_e - 2\pi/3)]/L \\
 i_{3e} &= [\psi_{3e} + \lambda_m (\theta_e - 4\pi/3)]/L
 \end{aligned}
 \tag{14}$$

The relevant values of λ_m are determined from a stored representation (such as a look-up table or predetermined analytical function) which expresses λ_m in terms of θ . Often, λ_m varies sinusoidally or trapezoidally with θ .

Alternatively, phase current may need to be determined from the more general Equation 2, using stored representations of L_{xx} and M_{xy} as functions of θ as well as λ_m as a function of θ .

The first phase current estimates (i_{1e} , i_{2e} and i_{3e}) from the first CURRENT ESTIMATION box are compared with the actual measured phase currents to give a first estimate of the current errors:

$$\begin{aligned}
 \Delta i_1 &= i_{1m} - i_{1e} \\
 \Delta i_2 &= i_{2m} - i_{2e} \\
 \Delta i_3 &= i_{3m} - i_{3e}
 \end{aligned}
 \tag{15}$$

Rotor Position Correction

The next stage in the predictor/corrector technique (see again the POSITION CORRECTION AND POSITION ESTIMATION & PREDICTION box) is to update the predicted rotor position value (the first estimate, θ_e) to yield a corrected rotor position value (the second estimate, θ_c). Assuming that the flux linkage estimate is correct, and that the errors in the estimated phase currents are due to errors in rotor position, then the corrected position is determined as that position which minimises the current errors. As can be seen from Equation 2, flux linkage is a function of several variables, such that $\psi = \psi(\theta, i_1, i_2, i_3)$. Changes in flux linkage occur as a result of changes in current and position, so that, for phase n:

$$\Delta \psi_{ne} = \frac{\partial \psi_{ne}}{\partial i_1} \Delta i_1 + \frac{\partial \psi_{ne}}{\partial i_2} \Delta i_2 + \frac{\partial \psi_{ne}}{\partial i_3} \Delta i_3 + \frac{\partial \psi_{ne}}{\partial \theta_e} \Delta \theta
 \tag{16}$$

where $\Delta \theta$ is the position error, equal to $\theta_e - \theta_c$. Given the above assumption that the flux linkage estimate is correct (that is, $\Delta \psi_{ne} = 0$), we have, for each phase:

$$\Delta \theta = \left(\frac{\partial \psi_{ne}}{\partial i_1} \Delta i_1 + \frac{\partial \psi_{ne}}{\partial i_2} \Delta i_2 + \frac{\partial \psi_{ne}}{\partial i_3} \Delta i_3 \right) / \left(- \frac{\partial \psi_{ne}}{\partial \theta_e} \right)
 \tag{17}$$

The partial derivatives of flux linkage with respect to current and rotor position are evaluated from stored representations (such as look-up tables or predetermined analytical functions) of the appropriate functions. For many types of motor, Equation 17 can be simplified by neglecting all the $\partial \psi / \partial i$ terms except $\partial \psi_{ne} / \partial i_n$.

It will be appreciated that, by determining the position error in dependence on the differential of flux linkage with respect to current, the effects of magnetic saturation (that is, non-linearities in the ψ versus i curve) can be taken into account.

Equation 17 yields a set of three position corrections ($\Delta \theta_1$, $\Delta \theta_2$, and $\Delta \theta_3$). A single revised position estimate is obtained by taking the average of the three corrections:

$$\Delta \theta_{(k)} = \frac{\Delta \theta_{1(k)} + \Delta \theta_{2(k)} + \Delta \theta_{3(k)}}{3}
 \tag{18}$$

At certain phase current levels and rotor positions some of the phases are better indicators of position error than others.

Therefore the position error averaging may incorporate weighting factors which are current and position dependent. The weighting factors may even be selected to neglect completely position correction information from certain phases at certain instants. A corrected position is calculated by adding the position error to the previous predicted position:

$$\theta_{(k)} = \theta_{e(k)} = \theta_{e(k-1)} + \Delta\theta_k \quad (19)$$

As clearly seen in Figure 2, an outer current loop is used to estimate the phase current; predicted position is utilised with estimated flux linkage for the current estimation. A position prediction is obtained by extrapolation from position data at previous time intervals.

Flux Linkage Correction

The final stage of the algorithm is to pass updated, corrected flux linkage values to the INTEGRATOR box. Such values need to be updated because the continuous estimation of flux linkage using an integration process creates unwanted effects in the flux linkage waveform. Measurement errors, due to noise, offsets and the temperature dependence of the winding resistance produce flux linkage errors, which then contribute to position estimation errors. However, some filtering and error correction are provided by updating the flux linkage estimates after the position estimate has been corrected. This updating is provided in a loop comprising the second CURRENT ESTIMATION, the FLUX LINKAGE CORRECTION and the INTEGRATOR boxes.

Updating proceeds as follows. First (see the second CURRENT ESTIMATION box) a second, revised estimate of the current errors (Δi_1 , Δi_2 and Δi_3) is made in the same way as the first estimate of the current errors (that is, using Equations 2 or 6, 14 and 15), except that the corrected rotor position (θ_e) is employed instead of the predicted position (θ_p). Then (see the FLUX LINKAGE CORRECTION box) the flux linkage estimates (ψ_{1e} , ψ_{2e} and ψ_{3e}) are updated using the corrected rotor position (θ_e) and the second, revised estimate of the current errors, in accordance with the principles underlying Equation 16. Thus, assuming that the errors in the flux linkage occur only because of current estimation errors, the corrections $\Delta\psi_{1e}$, $\Delta\psi_{2e}$ and $\Delta\psi_{3e}$ to the flux linkages are determined as follows:

$$\Delta\psi_{ne} = \frac{\partial\psi_{ne}}{\partial i_1} \Delta i_1 + \frac{\partial\psi_{ne}}{\partial i_2} \Delta i_2 + \frac{\partial\psi_{ne}}{\partial i_3} \Delta i_3 \quad n = 1, 2, 3 \quad (20)$$

The values of estimated flux linkage error are then passed to the INTEGRATOR box to update the integration.

A simplified procedure for updating the flux linkage is to set the Δi 's to zero in Equation 16 and determine the corrections to the flux linkages from the following equation:

$$\Delta\psi_{ne} = - \left(\frac{\partial\psi_{ne}}{\partial\theta_e} \right) \Delta\theta_n \quad n=1, 2, 3 \quad (21)$$

where θ_e and $\Delta\theta_n$ refer to the corrected rotor position. It will be appreciated that the alternative procedures outlined in relation to Equations 20 and 21 are in fact closely related.

MOTOR MODEL FOR THE MODIFIED EMBODIMENT

A modified version of the basic embodiment is now described. This version is applicable to any class of motor for which flux linkage is a function of rotor position. Considering firstly the model for the modified embodiment, the voltage equation for an n-phase machine may be written in the general form (compare with Equation 1 of the basic embodiment):

$$v_j = \sum_{q=1}^m R_q i_q + \frac{d\psi_j}{dt} \quad j = 1 \dots n \quad (22)$$

where v_j is the voltage across m series-connected phase windings carrying currents $i_1 \dots i_m$ and having resistances $R_1 \dots R_m$, and ψ_j is the total flux linking the m windings. Thus, for instance, in the star-connected three-phase winding

configuration shown in Figure 3 (the three windings having a common connection at node d), the three voltages v_j are v_{ab} , v_{bc} and v_{ca} respectively. The currents i_q and resistances R_q are the currents i_1 , i_2 and i_3 and the resistances R_1 , R_2 and R_3 respectively. Thus no voltage or current information is required to be measured at node d if the formulation of Equation 22 is used.

In general, ψ_j is a function of the n phase currents $i_1 \dots i_n$ and rotor position θ (compare with Equation 2 of the basic embodiment):

$$\psi_j = \psi_j(i_1, \dots, i_n, \theta) \quad (23)$$

ROTOR POSITION DETERMINATION FOR THE MODIFIED EMBODIMENT

The above general model can be applied in the following way to determine rotor position. Equation 22 can be rearranged to show how the flux linking the j th combination of m windings can be estimated, using measurements of the voltage, v_j , and phase currents $i_1 \dots i_m$ (compare with Equation 8 of the basic embodiment):

$$\psi_j = \int_{-\infty}^t \left(v_j - \sum_{q=1}^m R_q i_q \right) \cdot dt \quad (24)$$

For sampling at discrete time intervals of duration ΔT , Equation 24 may be re-written (compare with Equation 9 of the basic embodiment):

$$\psi_j(k) = \Delta T \left(v_j(k) - \sum_{q=1}^m R_q i_q(k) \right) + \psi_j(k-1) \quad k = 1, 2, \dots \quad (25)$$

so that the estimate of flux linkage $\psi_{j(k-1)}$ at time $(k-1)\Delta T$ can be utilised to estimate $\psi_{j(k)}$ at time $k\Delta T$.

Estimates of rotor position at time $k\Delta T$ may be obtained by fitting a polynomial function to rotor position values at previous time intervals and extrapolating in exactly the same manner as described in relation to the basic embodiment (see the description relating to the POSITION CORRECTION AND POSITION ESTIMATION & PREDICTION box).

At time instant k estimates of n flux linkages $\psi_{j(k)}$ ($j=1 \dots n$) are produced, together with a first estimate of rotor position, θ_e . For any motor, the functional relationship between flux linkage, current and position, expressed by Equation 23, can be predetermined. Therefore, in the present embodiment, given the estimates of flux linkages ψ_j and position θ_e , the set of phase currents i_{je} is estimated using stored representations of flux linkage as a function of rotor position and phase current. Where the functional relationship in Equation 23 is simple, this process may involve no more than the solution of a set of n simultaneous linear equations or an even simpler set of equations of the form given in Equations 14. However, more complex flux linkage functions may lead to a requirement for the iterative solution of a set of n non-linear equations.

It will be appreciated that, by estimating current using a stored representation of flux linkage as a function of phase current, the effects of magnetic saturation (that is, non-linearities in the ψ versus i curve) can be taken into account.

Given first estimates of phase current i_{je} , a first estimate of the current errors is determined by comparing estimated and measured currents (see the first CURRENT ESTIMATION box and compare with Equations 15):

$$\Delta i_j = i_{jm} - i_{je} \quad (26)$$

Errors in current arise from errors in flux linkage and rotor position. It can be deduced from Equation 23 that:

$$\Delta \psi_{je} = \left(\sum_{q=1}^n \left(\frac{\partial \psi_{je}}{\partial i_q} \right) \cdot \Delta i_q \right) + \left(\frac{\partial \psi_{je}}{\partial \theta} \right) \cdot \Delta \theta_j \quad (27)$$

where $\Delta\theta_j$ is the error in rotor position derived from consideration of winding set j . This equation is analogous to Equation 16.

Considering now the POSITION CORRECTION AND POSITION ESTIMATION & PREDICTION box, assuming initially that the set of flux linkage estimates is correct ($\Delta\psi_{je} = 0$), Equation 27 leads to a set of n position corrections $\Delta\theta_j$ ($j=1 \dots n$). A single position correction can be derived by combining these corrections. A number of options are available, ranging from simple averaging:

$$\Delta\theta = -\frac{1}{n} \sum_{j=1}^n \Delta\theta_j \quad (28)$$

to weighted averaging, with weighting dependent on instantaneous position and current. The second (corrected) estimate of rotor position at time $k\Delta T$ ($\theta_{e(k)}$) is then given by Equation 19.

Finally, considering the FLUX LINKAGE CORRECTION box, the set of flux linkage estimates may be updated by using the corrected position estimate ($\theta_{e(k)}$) to obtain a set of corrections $\Delta\psi_{je}$. From Equation 27, with $\Delta i_j = 0$ ($j=1 \dots n$):

$$\Delta\psi_{je} = \left(\frac{\partial \psi_{je}}{\partial \theta} \right) \cdot \Delta\theta \quad (29)$$

from which updated estimates of flux linkage can be determined and passed to the INTEGRATOR box.

It will be appreciated from the foregoing that the present invention requires some form of representation of various functions (for example, ψ as a function of i and θ) to be predetermined and then stored. The functions can be predetermined, for instance, by making the motor act as a generator and measuring the motional electromotive force which appears across the motor terminals. The representation of the function may, for instance, be a look-up table, or (if the function is amenable to such treatment) a Fourier series representation; the function may even be simply sinusoidal or trapezoidal, in which case its representation is trivial.

EXAMPLES

Experimental results obtained using the techniques of the present invention are now described with reference to Figures 4 and 5. The experiments were carried out on a commercial permanent-magnet brushless servo motor drive, with the following parameters:

phase inductance (L) = 3.12mH
 phase resistance (R) = 0.8 Ω
 motor and load inertia (J) = 0.008kg.m²
 no. motor poles pairs (p) = 4
 peak phase flux linkages due to the permanent magnet = 71mWb.t

Measurements of phase voltage, phase current and rotor position were recorded at intervals of 10 μ s as the drive accelerated from rest. The captured data was processed off-line using the techniques described above, thus allowing a comparison of the estimated and actual rotor position to be made.

Figures 4 show experimental results for a motor operated without current control and with a rectangular voltage waveform applied to each phase. The waveform in Figure 4a shows the voltage appearing across one phase and consists of constant voltage intervals, when the phase is excited, and intervals with near-constant slope, reflecting the magnet-induced electromotive force (emf), while the phase is unexcited. In the corresponding current waveform (Figure 4b) the current amplitude reduces between successive excitation intervals as the motor accelerates, causing the magnet-induced emf to increase in magnitude. Figure 4c shows the phase flux linkage estimate obtained by integrating ($v - Ri$) with respect to time for one phase, using the data shown in Figures 4a and 4b. As might be expected, the flux linkage characteristic is dominated by the permanent-magnet, which produces a sinusoidal variation. Superimposed on this variation, however, are step changes caused by phase switching. Corrected estimates of phase flux linkage, produced by the technique's application to the measured data, are shown in Figure 4d. For this particular set of results there exist only very small differences between the results in Figures 4c and 4d. The final two waveforms (Figures 4e and 4f) show measured and estimated rotor position as a function of time. Again there is very close agreement between these two sets of results, demonstrating that the position estimation technique is effective over the full speed range of

the drive.

Figures 5 show a similar set of results, but with a closed loop current controller causing modulation of the phase voltage (Figure 5a) to maintain the current constant in excited phases (Figure 5b). The drive accelerates from rest at a lower rate than in Figure 4, since current levels are lower, and the position estimation technique again operates effectively (Figure 5f).

EFFECTS OF MEASUREMENT ERRORS AND PARAMETER DEVIATIONS

The possible effects of measurement errors and parameter deviations on the quality of the results obtained using the present invention are now considered. Since the invention is implemented by calculating the flux linkage from the phase voltage and current, the performance of the invention depends on the quality and accuracy of the estimated flux linkages and measured currents. In addition to this, parameter deviations due to variations in temperature and saturation need to be considered.

Error terms in the flux linkage estimation and flux linkage variables due to measurement error and parameter variation may be expressed as follows:

$$\psi = \int (v - Ri) dt + e_1$$

$$\psi = Li - \lambda_m(\theta) + e_2 \quad (30)$$

where e_1 and e_2 are the errors due to measurement and parameter deviations respectively. The corruption sources on the flux linkage estimation may be classified under term e_1 as follows:

1. Measurement errors in the terminal quantities:-

- (a) phase shift in the measured values due to inaccuracies in the measurement system,
- (b) magnitude error due to conversion factors and gain,
- (c) offset in the measurement system, and
- (d) quantization error in the digital system.

2. Temperature effect on the winding resistance R.

The error term e_1 in Equations 30 mainly includes measurement errors. In both voltage and current measurement, one has to ensure that the measurement devices will not introduce a phase shift, offset or magnitude error. Another problem in the measurement system is the potentially noisy connection to the computer for carrying out the digital signal processing. The sensitive analog front end of the measurement devices can also be corrupted by a noisy computer connection. One solution is to place an isolation amplifier between the computer and the measurement system. However, the isolation amplifier could limit the performance of the system, particularly for high frequency measurements.

Moreover, in star-connected systems, if the current regulation in the third phase is reconstructed from the regulation in the other two phases, errors in the third phase current might be increased. The error in flux linkage estimation is mainly due to measurement errors, but it may not be separable from deviations in the winding resistance R.

The error term e_2 also includes current measurement error. However, it is mainly influenced by deviations in magnet flux linkage and winding inductance. For motors which have a large air gap, saturation effects caused by current level may be ignored. Otherwise, magnetic saturation can be taken into account in the manner described earlier. Deviations in the magnet flux linkages and changing back emf constant with temperature may also need to be taken into account.

The effects of parameter variations have been studied pursuant to the present invention with reference to initially measured motor parameters. In order to check the ability of the technique to perform in the presence of parameter variations, a test has been carried out changing the value of the winding resistance, the back emf constant, and the winding inductance within a $\pm 10\%$ range. It was found that changing the resistance value caused a small phase shift and noticeable dc offset in the estimated flux linkage waveform which could be overcome by the flux linkage correction. In one typical test, a change of 10% in the resistance of the windings caused a 0.7% error in rotor position during constant speed operation.

Changing the back emf constant caused a difference between estimated and corrected flux linkage. This deviation could be recovered by flux linkage correction. In a typical test, a 10% change in the back emf constant caused a 0.8% error in rotor position during constant speed operation.

Neither changing the value of the inductance nor changing the offset effect introduced any noticeable position error. However, again, any small errors can be eliminated by flux linkage correction.

It will be understood that the present invention has been described above purely by way of example, and that modifications of detail can be made within the scope of the invention as defined in the following claims.

Claims

1. A method of determining a rotor displacement parameter of the rotor of an electric motor (10), the method comprising the steps of:
 - measuring electrical characteristics of the motor (10) at given instants;
 - obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants;
 - obtaining an estimate of at least one of the electrical characteristics on the basis of said first estimate of said parameter and the measured electrical characteristics; and,
 - obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of at least one of the electrical characteristics and the measured value of said at least one electrical characteristic.
2. A method according to claim 1, wherein said measured electrical characteristics comprise the voltage and current of a phase of the electric motor (10), said at least one electrical characteristic being the phase current, and comprising the step of:
 - obtaining an estimate of the phase flux linkage on the basis of said measured voltage and current;
 - said estimate of the phase flux linkage being used with the first estimate of said parameter to provide the estimate of the phase current.
3. A method according to claim 2, comprising the further step of:
 - correcting the estimate of the phase flux linkage on the basis of the difference between the corrected estimate of said parameter and said first estimate of said parameter;
 - said corrected estimate of the phase flux linkage being used to provide the estimate of the phase current.
4. A method according to claim 2, comprising the further step of:
 - correcting the estimate of the phase flux linkage on the basis of the difference between the measured value of the phase current and the estimated value of the phase current;
 - said corrected estimate of the phase flux linkage being used to provide the estimate of the phase current.
5. A method according to any of claims 1 to 4, wherein the first estimate of said parameter is obtained on the basis of the values of the parameter at the three immediately preceding instants.
6. A method according to claim 5, wherein the updated value is predicted in accordance with an equation of the form $\hat{a}_k = 3a_{k-1} - 3a_{k-2} + a_{k-3}$, where \hat{a}_k is the updated value, and a_{k-1} , a_{k-2} and a_{k-3} are the values of the parameter at three preceding instants.
7. A method according to any of claims 1 to 6, wherein said parameter is the angular displacement of the rotor.
8. A method of determining a rotor displacement parameter for an electric motor (10), the method comprising the steps of:
 - measuring an electrical characteristic of the motor (10) at a given instant;
 - predicting a value representative of flux linkage from the characteristic;
 - correcting the predicted flux linkage value in dependence on the difference between the actual value of the characteristic and a value estimated using the predicted flux linkage value; and,
 - determining the rotor displacement parameter using the corrected flux linkage value.
9. A method according to claim 8, wherein the correction is determined in dependence on said difference multiplied

by the differential of flux linkage with respect to current.

10. A method according to claim 8 or claim 9, wherein the correction is determined from the difference between the actual and estimated values of such electrical characteristic for a plurality of phases of the motor (10).
11. A method according to any of claims 8 to 10, wherein values representative of the non-linear variation of flux linkage with current are stored and employed in the determination of the parameter value.
12. A method according to claim 11, wherein a value representative of current is estimated from flux linkage according to said stored representative values, and the parameter value is determined in dependence on the estimated current value.
13. A method according to any of claims 1 to 12, for determining the rotor displacement parameter for an electric motor (10) having a plurality of windings sharing a common connection, wherein the electrical characteristics are measured from points other than the common connection.
14. A method of controlling an electric motor (10), wherein the motor (10) is controlled in dependence on the value of the rotor displacement parameter determined in accordance with any of claims 1 to 13.
15. Apparatus for determining a rotor displacement parameter of a rotor of an electric motor (10), the apparatus comprising:
 - means (12,14) for measuring electrical characteristics of the motor (10) at given instants;
 - means (16) for obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants;
 - means (16) for obtaining an estimate of at least one of the electrical characteristics on the basis of said first estimate of said parameter and the measured electrical characteristics; and,
 - means (16) for obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of at least one of the electrical characteristics and the measured value of said at least one electrical characteristic.
16. Apparatus for determining a rotor displacement parameter of a rotor of an electric motor (10), the apparatus comprising:
 - means (12,14) for measuring the voltage and current of a phase of an electric motor (10) at given instants;
 - means (16) for obtaining a first estimate of said parameter on the basis of values of the parameter at previous instants;
 - means (16) for obtaining an estimate of the phase flux linkage on the basis of said measured voltage and current;
 - means (16) for obtaining an estimate of the phase current on the basis of said first estimate of said parameter and the estimate of the phase flux linkage; and,
 - means (16) for obtaining a corrected estimate of said parameter by correcting said first estimate of said parameter on the basis of the difference between said estimate of the phase current and the measured value of the phase current.
17. Apparatus for determining a rotor displacement parameter for an electric motor (10), the apparatus comprising:
 - means (12,14) for measuring an electrical characteristic of the motor (10) at a given instant;
 - means (16) for predicting a value representative of flux linkage from the characteristic;
 - means (16) for correcting the predicted flux linkage value in dependence on the difference between the actual value of the characteristic and a value estimated using the predicted flux linkage value; and,
 - means (16) for determining the rotor displacement parameter using the corrected flux linkage value.
18. Apparatus according to claim 17, wherein the correcting means is arranged to determine the correction in dependence on said difference multiplied by the differential of flux linkage with respect to current.
19. Apparatus according to claim 17 or claim 18, wherein the determining means is arranged to determine the parameter in dependence on the differentials with respect to current of the flux linkages for a plurality of phases of the

motor (10).

20. Apparatus according to any of claims 17 to 19, comprising means for storing values representative of the non-linear variation of flux linkage with current, said values being employed by the determining means in the determination of the parameter value.
21. Apparatus for controlling an electric motor (10), including means (18) for controlling a motor (10) in dependence on the value of a rotor displacement parameter and apparatus for determining the rotor displacement parameter according to any of claims 15 to 20.
22. Apparatus according to any of claims 15 to 21, including an electric motor (10).

Patentansprüche

1. Verfahren zum Bestimmen eines Rotorverstellparameters des Rotors eines Elektromotors (10), wobei das Verfahren die Schritte aufweist:

Messen elektrischer Charakteristiken des Motors (10) zu gegebenen Zeitpunkten;
 Erhalten einer ersten Schätzung des Parameters auf der Basis von Werten des Parameters zu vorherigen Zeitpunkten;
 Erhalten einer Schätzung von zumindest einer der elektrischen Charakteristiken auf der Basis der ersten Schätzung des Parameters und der gemessenen elektrischen Charakteristiken; und
 Erhalten einer korrigierten Schätzung des Parameters durch Korrigieren der ersten Schätzung des Parameters auf der Basis der Differenz zwischen der Schätzung von zumindest einer der elektrischen Charakteristiken und dem gemessenen Wert der zumindest einen elektrischen Charakteristik.

2. Verfahren nach Anspruch 1, worin die gemessenen elektrischen Charakteristiken die Spannung und den Strom einer Phase des Elektromotors (10) umfassen, wobei zumindest eine elektrische Charakteristik der Phasenstrom ist, mit dem Schritt:

Erhalten einer Schätzung der Phasenflußverkettung auf der Basis der gemessenen Spannung und des gemessenen Stroms;
 wobei die Schätzung der Phasenflußverkettung mit der ersten Schätzung des Parameters verwendet wird, um die Schätzung des Phasenstroms zu liefern.

3. Verfahren nach Anspruch 2, mit dem weiteren Schritt:

Korrigieren der Schätzung der Phasenflußverkettung auf der Basis der Differenz zwischen der korrigierten Schätzung des Parameters und der ersten Schätzung des Parameters;
 wobei die korrigierte Schätzung der Phasenflußverkettung verwendet wird, um die Schätzung des Phasenstroms zu liefern.

4. Verfahren nach Anspruch 2, mit dem weiteren Schritt:

Korrigieren der Schätzung der Phasenflußverkettung auf der Basis der Differenz zwischen dem gemessenen Wert des Phasenstroms und dem geschätzten Wert des Phasenstroms;
 wobei die korrigierte Schätzung der Phasenflußverkettung verwendet wird, um die Schätzung des Phasenstroms zu liefern.

5. Verfahren nach einem der Ansprüche 1 bis 4, worin die erste Schätzung des Parameters auf der Basis der Werte des Parameters zu drei unmittelbar vorhergehenden Zeitpunkten erhalten wird.

6. Verfahren nach Anspruch 5, worin der aktualisierte Wert gemäß einer Gleichung der Form $\underline{a}_k = 3a_{k-1} - 3a_{k-2} + a_{k-3}$ vorhergesagt wird, worin \underline{a}_k der aktualisierte Wert ist und a_{k-1} , a_{k-2} und a_{k-3} die Werte des Parameters zu drei vorhergehenden Zeitpunkten sind.

7. Verfahren nach einem der Ansprüche 1 bis 6, worin der Parameter die Winkelverstellung des Rotors ist.

8. Verfahren zum Bestimmen eines Rotorverstellparameters für einen Elektromotor (10), wobei das Verfahren die Schritte aufweist:

Messen einer elektrischen Charakteristik des Motors (10) zu einem gegebenen Zeitpunkt;
Vorhersagen eines eine Flußverkettung darstellenden Wertes aus der Charakteristik;
Korrigieren des vorhergesagten Flußverkettungswertes in Abhängigkeit von der Differenz zwischen dem tatsächlichen Wert der Charakteristik und einem unter Verwendung des vorhergesagten Flußverkettungswertes geschätzten Wertes; und
Bestimmen des Rotorverstellparameters unter Verwendung des korrigierten Flußverkettungswertes

9. Verfahren nach Anspruch 8, worin die Korrektur in Abhängigkeit von der mit der differentiellen Ableitung der Flußverkettung nach dem Strom multiplizierten Differenz bestimmt wird.

10. Verfahren nach Anspruch 8 oder Anspruch 9, worin die Korrektur aus der Differenz zwischen den tatsächlichen und geschätzten Werten einer solchen elektrischen Charakteristik für mehrere Phasen des Motors (10) bestimmt wird.

11. Verfahren nach einem der Ansprüche 8 bis 10, worin die die nicht-lineare Variation einer Flußverkettung mit einem Strom darstellenden Werte gespeichert und bei der Bestimmung des Parameterwertes verwendet werden.

12. Verfahren nach Anspruch 11, worin ein einen Strom darstellender Wert aus einer Flußverkettung gemäß den gespeicherten darstellenden Werten geschätzt wird und der Parameterwert in Abhängigkeit von dem geschätzten Stromwert bestimmt wird.

13. Verfahren nach einem der Ansprüche 1 bis 12, zum Bestimmen des Rotorverstellparameters für einen Elektromotor (10) mit mehreren Wicklungen, die sich eine gemeinsame Verbindung teilen, worin die elektrischen Charakteristiken von anderen Punkten als der gemeinsamen Verbindung gemessen werden.

14. Verfahren zum Steuern eines Elektromotors (10), worin der Motor (10) in Abhängigkeit von dem Wert des gemäß einem der Ansprüche 1 bis 13 bestimmten Rotorverstellparameters gesteuert wird.

15. Vorrichtung zum Bestimmen eines Rotorverstellparameters eines Rotors eines Elektromotors (10) mit:

einer Einrichtung (12,14) zum Messen elektrischer Charakteristiken des Motors (10) zu gegebenen Zeitpunkten;
einer Einrichtung (16) zum Erhalten einer ersten Schätzung des Parameters auf der Basis von Werten des Parameters zu vorhergehenden Zeitpunkten;
einer Einrichtung (16) zum Erhalten einer Schätzung von zumindest einer der elektrischen Charakteristiken auf der Basis der ersten Schätzung des Parameters und der gemessenen elektrischen Charakteristiken; und
einer Einrichtung (16) zum Erhalten einer korrigierten Schätzung des Parameters durch Korrigieren der ersten Schätzung des Parameters auf der Basis der Differenz zwischen der Schätzung von zumindest einer der elektrischen Charakteristiken und dem gemessenen Wert der zumindest einen elektrischen Charakteristik.

16. Vorrichtung zum Bestimmen eines Rotorverstellparameters eines Rotors eines Elektromotors (10) mit:

einer Einrichtung (12, 14) zum Messen der Spannung und des Stroms einer Phase eines Elektromotors (10) zu gegebenen Zeitpunkten;
einer Einrichtung (16) zum Erhalten einer ersten Schätzung des Parameters auf der Basis von Werten des Parameters zu vorherigen Zeitpunkten;
einer Einrichtung (16) zum Erhalten einer Schätzung der Phasenflußverkettung auf der Basis der gemessenen Spannung und des gemessenen Stroms;
einer Einrichtung (16) zum Erhalten einer Schätzung des Phasenstroms auf der Basis der ersten Schätzung des Parameters und der Schätzung der Phasenflußverkettung; und
einer Einrichtung (16) zum Erhalten einer korrigierten Schätzung des Parameters durch Korrigieren der ersten Schätzung des Parameters auf der Basis der Differenz zwischen der Schätzung des Phasenstroms und dem gemessenen Wert des Phasenstroms.

17. Vorrichtung zum Bestimmen eines Rotorverstellparameters für einen Elektromotor (10) mit:

einer Einrichtung (12, 14) zum Messen einer elektrischen Charakteristik des Motors (10) zu einem gegebenen Zeitpunkt;
 einer Einrichtung (16) zum Vorhersagen eines eine Flußverkettung darstellenden Wertes aus der Charakteristik;
 einer Einrichtung (16) zum Korrigieren des vorhergesagten Flußverkettungswertes in Abhängigkeit von der Differenz zwischen dem tatsächlichen Wert der Charakteristik und einem unter Verwendung des vorhergesagten Flußverkettungswertes geschätzten Wertes; und
 einer Einrichtung (16) zum Bestimmen des Rotorverstellparameters unter Verwendung des korrigierten Flußverkettungswertes.

18. Vorrichtung nach Anspruch 17, worin die Korrigiereinrichtung angeordnet ist, um die Korrektur in Abhängigkeit von der mit der differentiellen Ableitung der Flußverkettung nach dem Strom multiplizierten Differenz zu bestimmen.
19. Vorrichtung nach Anspruch 17 oder Anspruch 18, worin die Bestimmungseinrichtung angeordnet ist, um den Parameter in Abhängigkeit von den differentiellen Ableitungen nach dem Strom der Flußverkettungen für eine Vielzahl von Phasen des Motors (10) zu bestimmen.
20. Vorrichtung nach einem der Ansprüche 17 bis 19, mit einer Einrichtung zum Speichern von Werten, die die nicht-lineare Variation einer Flußverkettung mit dem Strom darstellen, wobei die Werte durch die Bestimmungseinrichtung bei der Bestimmung des Parameterwertes verwendet werden.
21. Vorrichtung zum Steuern eines Elektromotors (10), die eine Einrichtung (18) zum Steuern eines Motors (10) in Abhängigkeit von dem Wert eines Rotorverstellparameters und eine Vorrichtung zum Bestimmen des Rotorverstellparameters nach einem der Ansprüche 15 bis 20 enthält.
22. Vorrichtung nach einem der Ansprüche 15 bis 21, die einen Elektromotor (10) enthält.

Revendications

1. Procédé pour déterminer un paramètre de déplacement de rotor du rotor d'un moteur électrique (10), le procédé comportant les étapes consistant à :
 mesurer des caractéristiques électriques du moteur (10) à des instants donnés,
 obtenir une première estimation dudit paramètre sur la base de valeurs prises par le paramètre à des instants précédents,
 obtenir une estimation d'au moins l'une des caractéristiques électriques sur la base de ladite première estimation dudit paramètre et des caractéristiques électriques mesurées, et
 obtenir une estimation corrigée dudit paramètre en corrigeant ladite première estimation dudit paramètre sur la base de la différence existant entre ladite estimation d'au moins l'une des caractéristiques électriques et la valeur mesurée de ladite au moins une caractéristique électrique.
2. Procédé selon la revendication 1, dans lequel lesdites caractéristiques électriques mesurées comprennent la tension et le courant d'une phase du moteur électrique (10), ladite au moins une caractéristique électrique étant le courant de phase, et comportant l'étape consistant à :
 obtenir une estimation de l'enchaînement du flux de phase sur la base de ladite tension et dudit courant mesurés,
 ladite estimation de l'enchaînement du flux de phase étant utilisée en association avec la première estimation dudit paramètre pour obtenir l'estimation du courant de phase.
3. Procédé selon la revendication 2, comportant en outre l'étape consistant à :
 corriger l'estimation de l'enchaînement du flux de phase sur la base de la différence existant entre l'estimation corrigée dudit paramètre et ladite première estimation dudit paramètre,
 ladite estimation corrigée de l'enchaînement du flux de phase étant utilisée pour obtenir l'estimation du courant de phase.

4. Procédé selon la revendication 2, comportant en outre l'étape consistant à :

corriger l'estimation de l'enchaînement du flux de phase sur la base de la différence existant entre la valeur mesurée du courant de phase et la valeur estimée du courant de phase, ladite estimation corrigée de l'enchaînement du flux de phase étant utilisée pour obtenir l'estimation du courant de phase.

5. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel la première estimation dudit premier paramètre est obtenue sur la base des valeurs prises par le paramètre aux trois instants immédiatement précédents.

6. Procédé selon la revendication 5, dans lequel la valeur actualisée est prédite en utilisant une équation de la forme $\hat{a}_k = 3a_{k-1} - 3a_{k-2} + a_{k-3}$, où \hat{a}_k est la valeur actualisée, et a_{k-1} , a_{k-2} et a_{k-3} sont les valeurs prises par le paramètre aux trois instants précédents.

7. Procédé selon l'une quelconque des revendications 1 à 6, dans lequel ledit paramètre est le déplacement angulaire du rotor.

8. Procédé pour déterminer un paramètre de déplacement de rotor pour un moteur électrique (10), le procédé comportant les étapes consistant à :

mesurer une caractéristique électrique du moteur (10) à un instant donné, prédire une valeur représentative de l'enchaînement du flux à partir de la caractéristique, corriger la valeur prédite de l'enchaînement du flux en se basant sur la différence existant entre la valeur réelle de la caractéristique et une valeur estimée en utilisant la valeur prédite de l'enchaînement du flux, et déterminer le paramètre de déplacement du rotor en utilisant la valeur corrigée de l'enchaînement du flux.

9. Procédé selon la revendication 8, dans lequel la correction est déterminée sur la base de ladite différence, multipliée par la dérivée de l'enchaînement du flux par rapport au courant.

10. Procédé selon la revendication 8 ou 9, dans lequel la correction est déterminée à partir de la différence existant entre les valeurs réelle et estimée d'une telle caractéristique électrique pour plusieurs phases du moteur (10).

11. Procédé selon l'une quelconque des revendications 8 à 10, dans lequel des valeurs représentatives de la variation non-linéaire de l'enchaînement du flux en fonction du courant sont mémorisées et sont utilisées dans la détermination de la valeur du paramètre.

12. Procédé selon la revendication 11, dans lequel une valeur représentative du courant est estimée à partir de l'enchaînement du flux sur la base desdites valeurs représentatives mémorisées, et la valeur du paramètre est déterminée sur la base de la valeur estimée du courant.

13. Procédé selon l'une quelconque des revendications 1 à 12, pour déterminer le paramètre de déplacement de rotor, pour un moteur électrique (10) comportant plusieurs enroulements partageant une connexion commune, dans lequel les caractéristiques électriques sont mesurées à partir de points autres que la connexion commune.

14. Procédé pour commander un moteur électrique (10), dans lequel le moteur (10) est commandé sur la base de la valeur du paramètre de déplacement de rotor déterminée conformément à l'une quelconque des revendications 1 à 13.

15. Dispositif pour déterminer un paramètre de déplacement de rotor d'un rotor de moteur électrique (10), le dispositif comportant :

des moyens (12, 14) pour mesurer des caractéristiques électriques du moteur (10) à des instants donnés, des moyens (16) pour obtenir une première estimation dudit paramètre sur la base de valeurs prises par le paramètre à des instants précédents, des moyens (16) pour obtenir une estimation d'au moins l'une des caractéristiques électriques sur la base de ladite première estimation dudit premier paramètre et des caractéristiques électriques mesurées, et des moyens (16) pour obtenir une estimation corrigée dudit paramètre en corrigeant ladite première estimation dudit premier paramètre sur la base de la différence existant entre ladite estimation d'au moins l'une des

caractéristiques électriques et la valeur mesurée de ladite au moins une caractéristique électrique.

16. Dispositif pour déterminer un paramètre de déplacement de rotor d'un rotor de moteur électrique (10), le dispositif comportant :

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des moyens (12, 14) pour mesurer la tension et le courant d'une phase d'un moteur électrique (10) à des instants donnés,

des moyens (16) pour obtenir une première estimation dudit paramètre sur la base de valeurs prises par le paramètre à des instants précédents,

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des moyens (16) pour obtenir une estimation de l'enchaînement du flux de phase sur la base de ladite tension et dudit courant mesurés,

des moyens (16) pour obtenir une estimation du courant de phase sur la base de ladite première estimation dudit paramètre et de l'estimation de l'enchaînement du flux de phase, et

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des moyens (16) pour obtenir une estimation corrigée dudit paramètre en corrigeant ladite première estimation dudit paramètre sur la base de la différence existant entre ladite estimation du courant de phase et la valeur mesurée du courant de phase.

17. Dispositif pour déterminer un paramètre de déplacement de rotor pour un moteur électrique (10), le dispositif comportant :

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des moyens (12, 14) pour mesurer une caractéristique électrique du moteur (10) à un instant donné,

des moyens (16) pour prédire une valeur représentative de l'enchaînement du flux à partir de la caractéristique,

des moyens (16) pour corriger la valeur prédite de l'enchaînement du flux sur la base de la différence existant entre la valeur réelle de la caractéristique et une valeur estimée en utilisant la valeur prédite de l'enchaînement

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du flux, et

des moyens (16) pour déterminer le paramètre de déplacement du rotor en utilisant la valeur corrigée de l'enchaînement.

18. Dispositif selon la revendication 17, dans lequel les moyens de correction sont conçus pour déterminer la correction sur la base de ladite différence, multipliée par la dérivée de l'enchaînement du flux par rapport au courant.

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19. Dispositif selon la revendication 17 ou 18, dans lequel les moyens de détermination sont conçus pour déterminer le paramètre sur la base des dérivées par rapport au courant des enchaînements de flux, pour plusieurs phases du moteur (10).

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20. Dispositif selon l'une quelconque des revendications 17 à 19, comportant des moyens pour mémoriser des valeurs représentatives de la variation non-linéaire de l'enchaînement du flux en fonction du courant, lesdites valeurs étant utilisées par les moyens de détermination dans la détermination de la valeur du paramètre.

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21. Dispositif pour commander un moteur électrique (10) comportant des moyens (18) pour commander un moteur (10) sur la base de la valeur d'un paramètre de déplacement de rotor et un dispositif pour déterminer le paramètre de déplacement de rotor selon l'une quelconque des revendications 15 à 20.

22. Dispositif selon l'une quelconque des revendications 15 à 21, comportant un moteur électrique (10).

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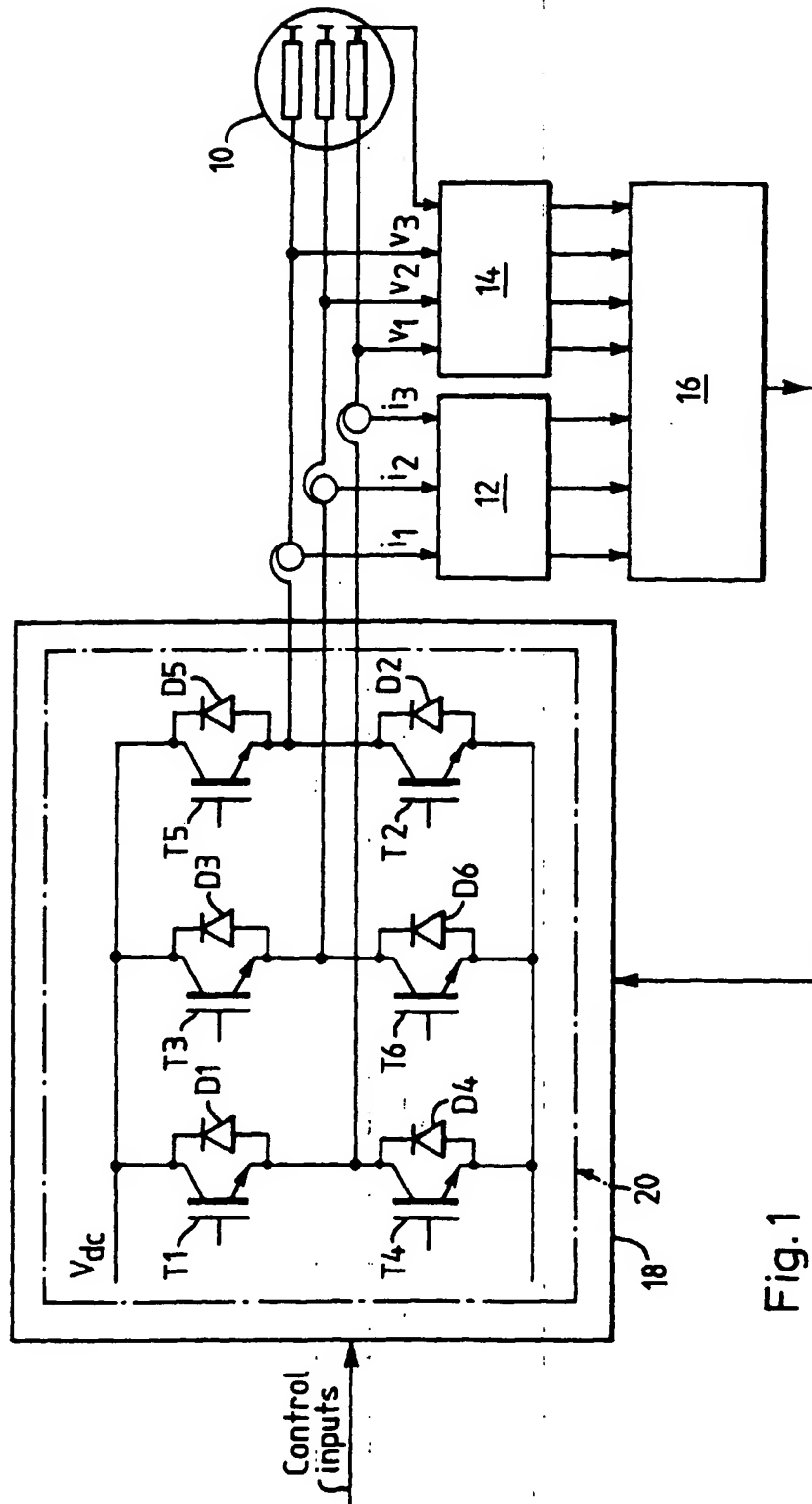


Fig.1

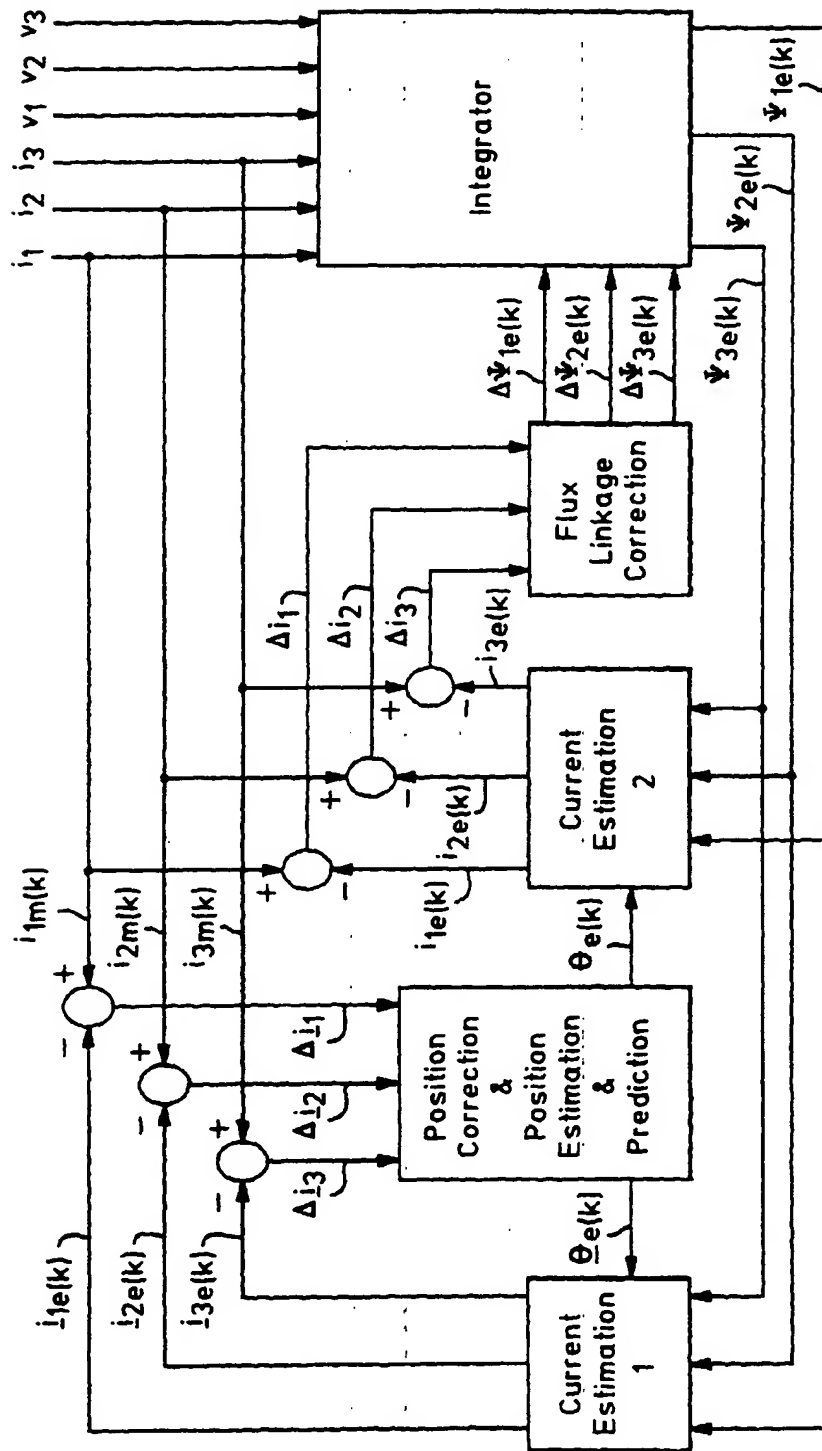


Fig.2

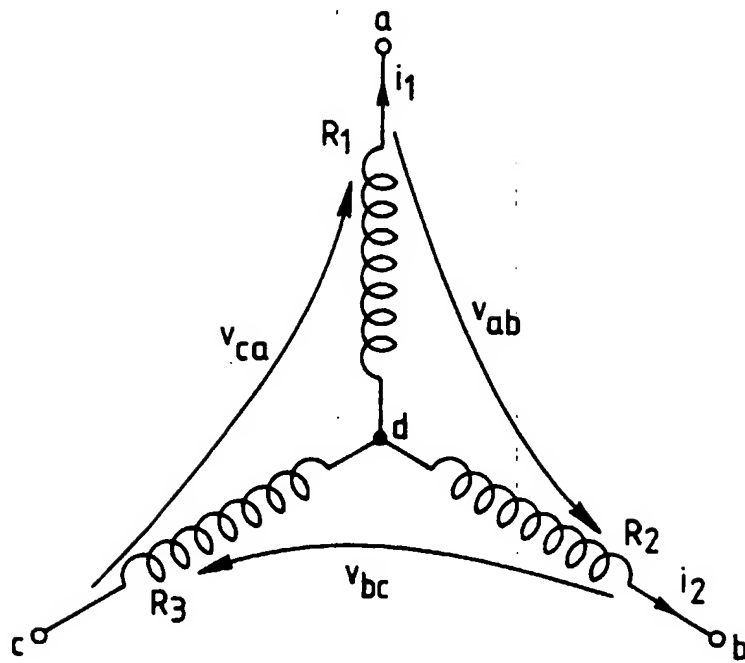


Fig.3

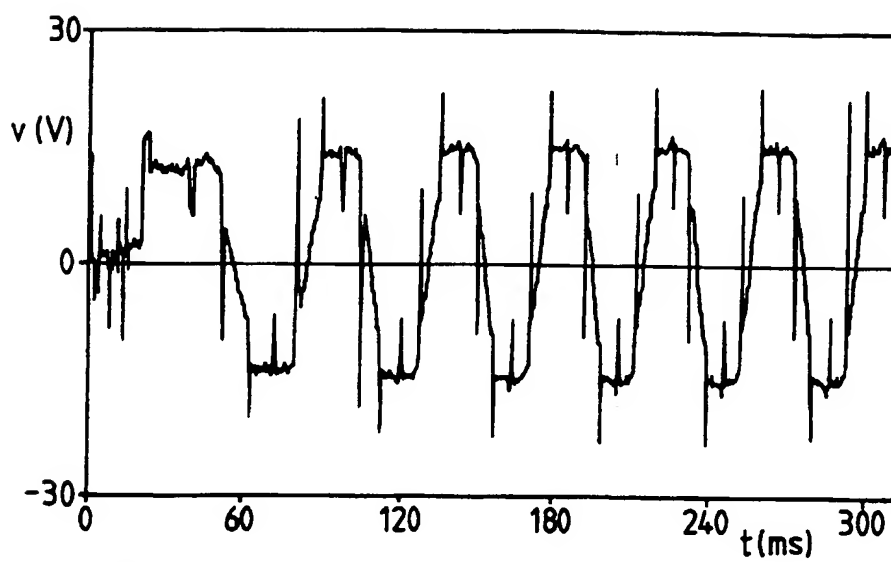


Fig.4a

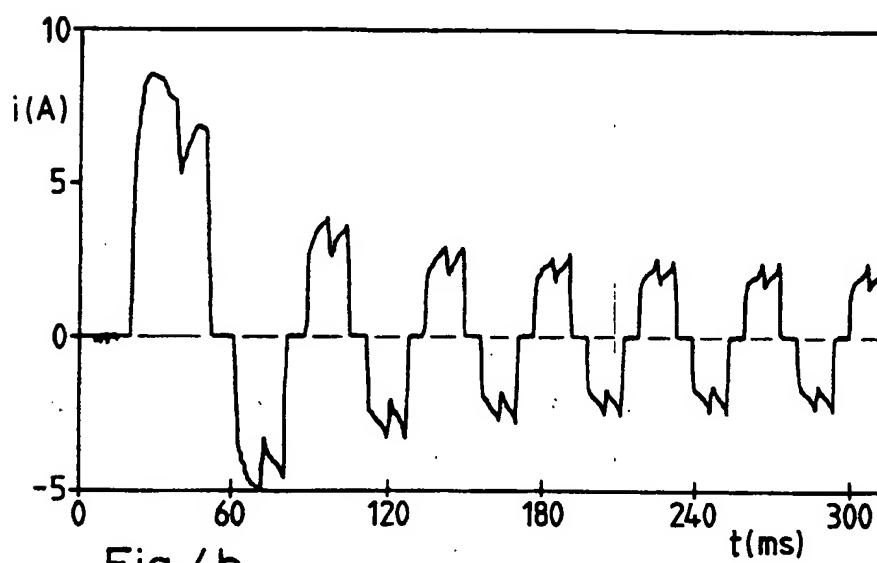


Fig.4b

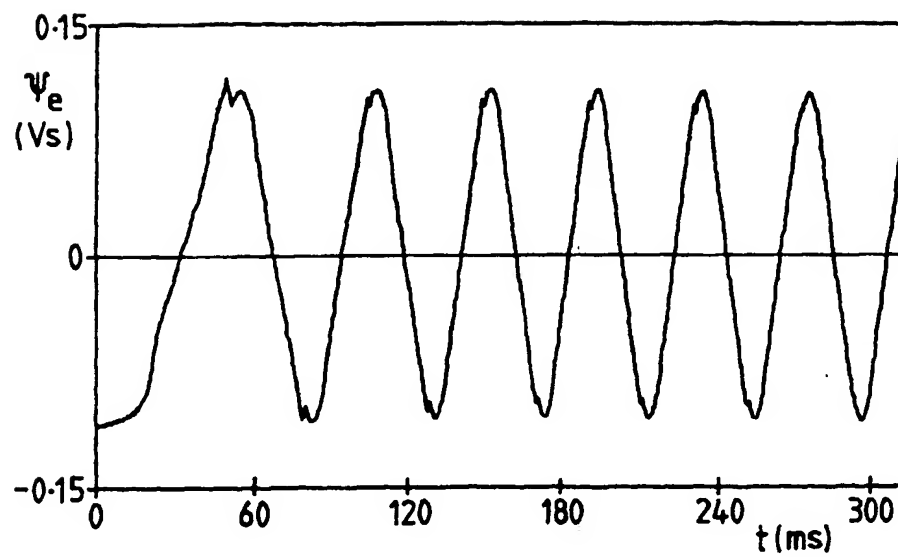


Fig.4c

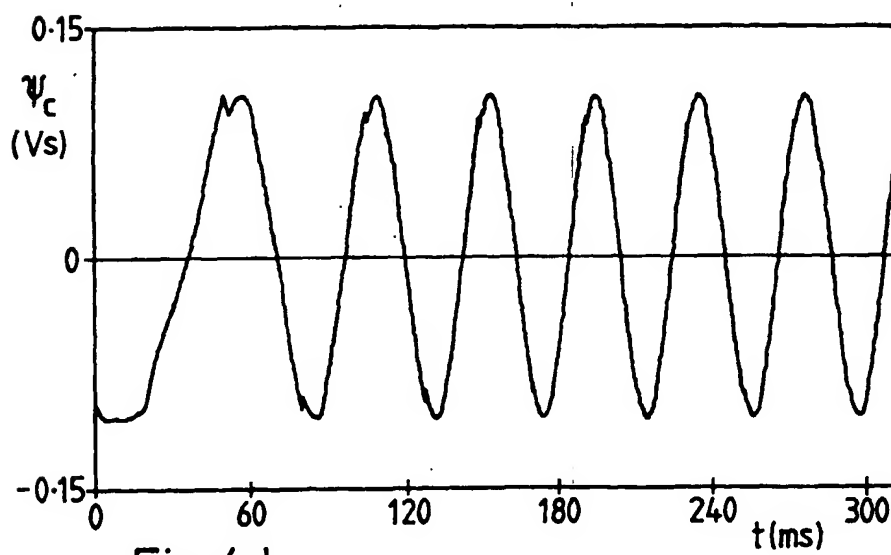


Fig.4d

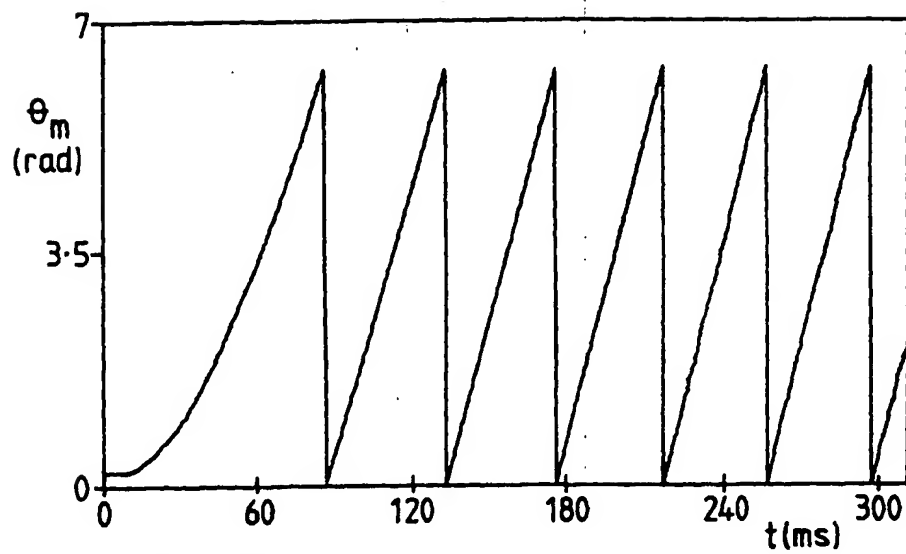


Fig. 4e

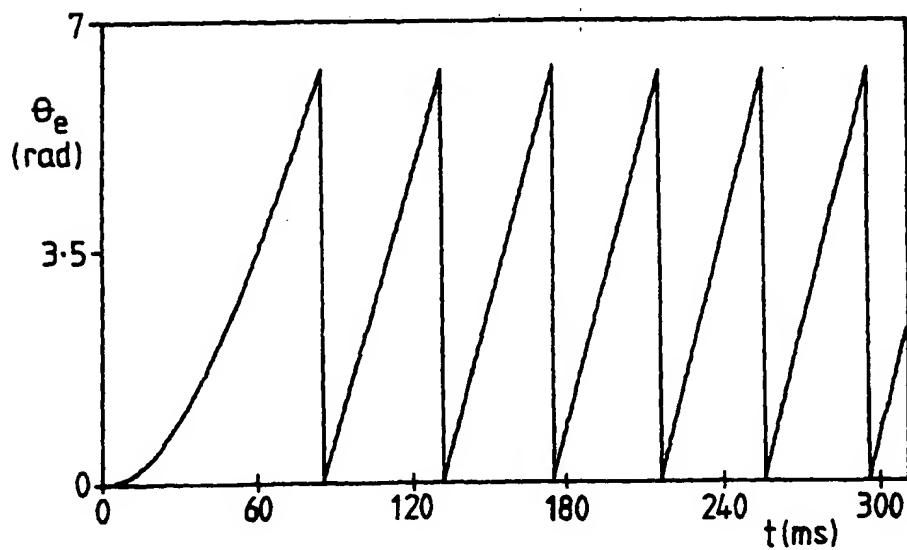


Fig. 4f

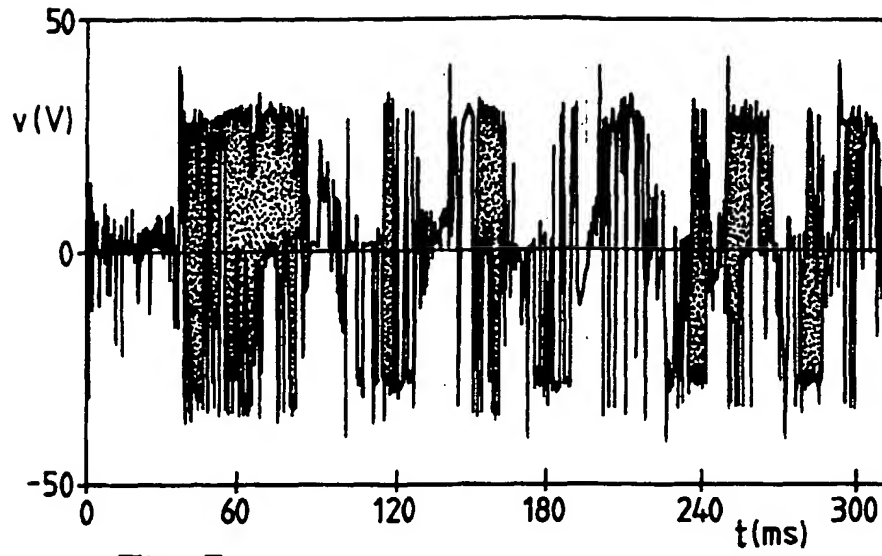


Fig. 5a

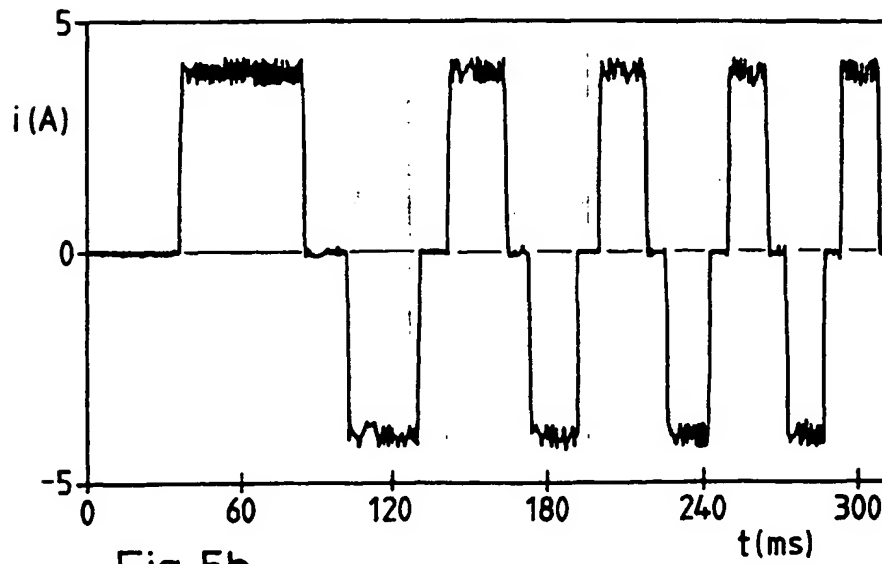


Fig. 5b

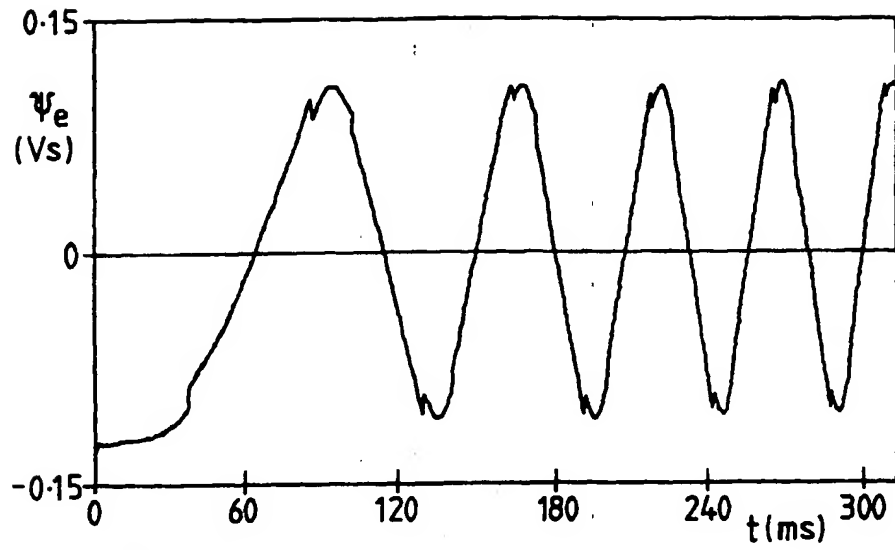


Fig. 5c

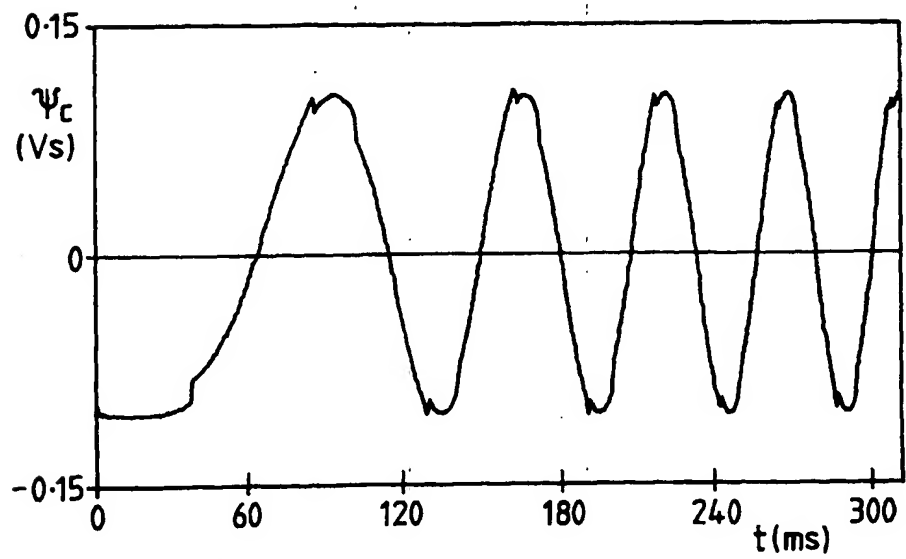


Fig. 5d

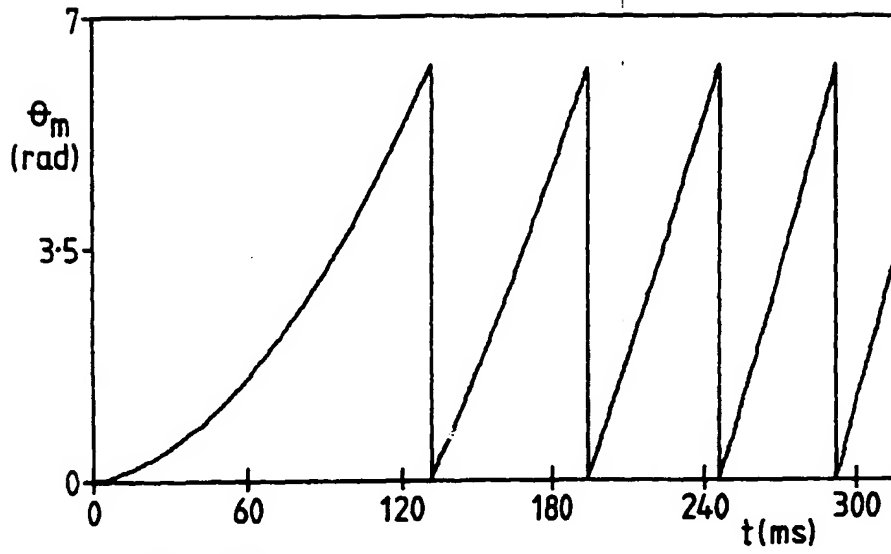


Fig. 5e

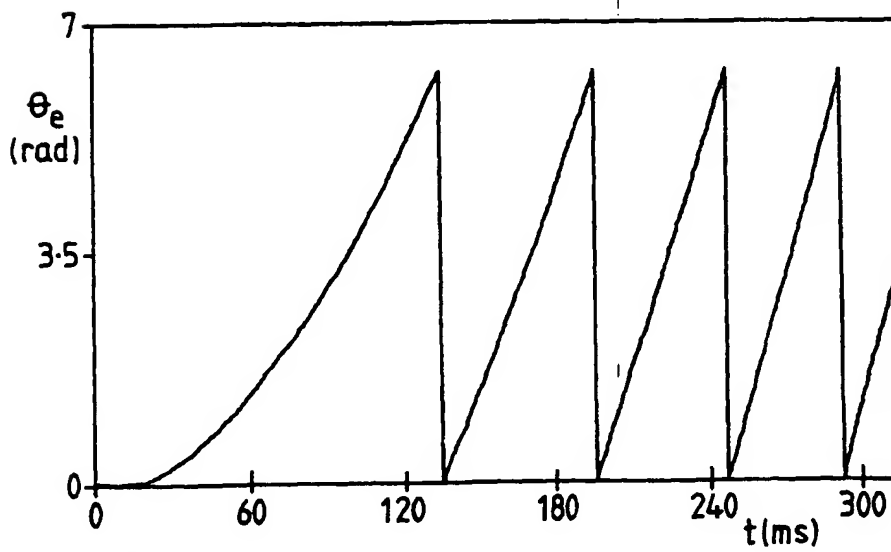


Fig. 5f

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